Mobile Positioning Without GPS in CDMA2000 1X

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Abstract

Mobile positioning measurement is the most important technology for Location Based Services in the cellular networks. Generally, we are expecting to use GPS to guarantee high accuracy of the mobile position.

A CDMA network-based technique for the Mobile Station position calculation needs to be implemented in the cdma2000 network whether the handsets have GPS or not.

The most reliable methods of the network-based location technologies are based on the estimation of time of signal traveling between MS and BTS in a network whose coordinates are identified. Other signal parameters such as the power of the receivec signal and the signal arrival direction cannot be used as main data for a location system because adoption of only the signal parameters will not meet the FCC requirements. In practice, the estimates of the time of signal propagation between MS and BTS always have errors resulting from low-resolution power of measurements and multipath signal propagation.

This paper describes the combined network-based location technology in the cdma2000 1x necessary to meet US FCC requirements. The issues of a calibration table and statistic processing based on the pilot strength as well as combined network-based location technologies(TOA/ TDOA) will help to achieve higher location accuracy than specified in the US FCC Rule.

1. Introduction

U.S. Federal Communication Committee(FCC) E911 Regulation [1] specifies that every 911 call originated by Mobile Station(MS) should be located so that the call can be routed to an appropriate emergency 911 Public Safety Answering Point(PSAP) and the PSAP can receive an accurate information about the MS location. U.S. FCC E911 Regulation phase II requires 50m accuracy with 67% probability for MS with Global Positioning System(GPS) and 100m accuracy with 67% probability for MS without GPS when every emergency 911 call is originated. The requirements defined in the U.S. FCC E911 Regulation were to be implemented by October 1, 2001. This location estimate may be performed by the GPS built in the handset, the cdma 2000 infrastructure or a hybrid of the cdma2000 and the GPS.

To meet the requirements of the FCC E911 Regulation, a separate location server for the Mobile Station position calculation needs to be added to the cdma2000 network whether the handsets have GPS or not. The network-based mode refers to the mobile positioning approach applied to the handsets without GPS. The network-based E911 services can be provided to the handsets without GPS receiver in 5 basic methods and some hybrid methods. The 5 basic technologies are Signal Strength [2] Angle of Arrival(AOA) [3], Time of Arrival(TOA), Time Difference of Arrival (TDOA) [4], Multipath Finger-printing while the hybrid technologies include AOA/TOA and AOA/TDOA.

Figure 1 illustrates the generic network architecture of the network-based location technologies. There is a Signal Collection System(SCS) co-located with the

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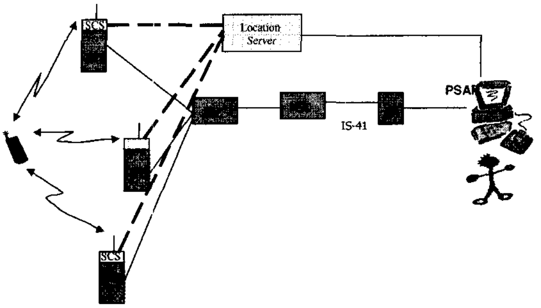


(Figure 1) Generic Network Architecture of Network-based Location Technologies

Base Station Subsystem(BTS). The SCS and the BTS share the same antenna. The SCS is directly connected to the Location Server(LS), which in turn is connected to the PSAP in the case of an E-911 service, or to the Location Services Service Provider.

The function of the SCS is to collect the signals received from the MS and perform some pre-processing if necessary. The LS performs the final computation/processing of the received signals and stores the latitude/longitude and ESN of the MS. This information can be accessed by the PSAP personnel and/or the Location Services Service Provider.

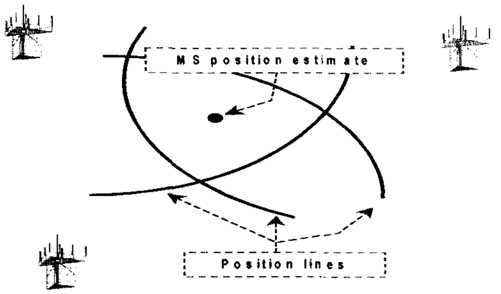
The network-based location technology can be implemented based on either of Signal Strength, AOA, TOA, TDOA and Multipath Finger-printing, or their combinations.

2. Hybrid Network-based Location Algorithm

2.1 Estimation of existing network-based algorithm

The most reliable methods of the network-based location technologies are TOA/TDOA based on the estimation of time of signal traveling between MS and BTS in a network whose coordinates are identified.

Other signal parameters such as the power of the received signal and the signal arrival direction cannot be used as main data for a location system because adoption of only the signal parameters will not meet the FCC requirements.



(Figure 2) TOA mehod

In practice, the estimates of the time of signal propagation between MS and BTS always have errors resulting from low-resolution power of measurements and multipath signal propagation. Therefore, lines of position are normally not intersected at one point and the center of gravity of the obtained figure is selected as an estimate of MS position [8](Figure 2).

2.2 Hybrid network-based algorithm

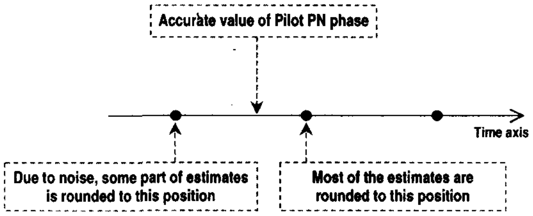
In the cdma2000 1x, PN code synchronization module is used for acquiring system time and performing synchronized demodulation. Its functions include a PN code acquisition to decide initial PN code phase and a PN code tracking within 1 chip period. Especially, on the forward link, the pilot channel is transmitted from BS to achieve this purpose.

The estimates of Pilot PN phase available in the cdma2000 1x network are determined with low resolution (1 chip), which corresponds to uncertainty of MS position of about 300 meters[18]. Therefore, one chip-based location calculation cannot meet the FCC requirements unless additional processing of these estimates is performed. The estimates of Pilot PN phase available in the cdma2000 1x network are intended for the handoff purposes, so MS does not compensate for the multipath error when Pilot PN phase is estimated. As a result, the estimates of Pilot PN phase obtained via different BTSs can have different reliability. Hence, in order to meet the FCC requirements, it is necessary to carry out statistic processing of several serially obtained estimates of Pilot PN phase in Location Server. If, during processing of the estimates of Pilot PN phase in the location server, an enhanced reliability of estimates is taken into account and averaging of the measured values is performed to improve resolution, the location accuracy can meet the FCC requirements.

- Estimate resolution improvement

If an actual value of Pilot PN phase is not an integer number of chips, it can be rounded to the integer(Figure 3).

Due to noise, rounding to both smaller and larger directions can be performed, but rounding to the smaller direction is most probable. If several serial estimates are averaged, it is possible to obtain the estimate of Pilot PN phase with the accuracy that would be better than that of the initial resolution.



(Figure 3) Estimation of resolution

2.2.1 Estimation of pilot PN phase measurement reliability

The variance of Pilot PN phase estimates increases due to multipath. The more the location server estimates the Pilot PN phase consecutively, the higher the reliability of the measured Pilot PN phase becomes.

Also, Pilot Strength can be used for estimation of measurement reliability.

2.2.2 Determination of required number of pseudo-range estimates

In practical implementation of the algorithm, the number of estimates should be optimized. Insufficient number of estimates will not allow us to meet the FCC requirements and redundant estimates result in traffic growth.

It is necessary to determine the minimum required number of Pilot PN phase estimates based on the calibrating table.

2.2.3 Use of calibrating table

A calibrating table can be used to improve location accuracy. The calibrating table should contain at least the estimate of maximum multipath error for each BTS sector. The method of filling up the calibrating table and the exact list of required data are subject to related specifications. It is desirable to use the calibrating table in order to determine Pilot PN Phase measurement reliability and compensate for systematic errors.

2.3 Comparison between the proposed solutions and conventional solutions

Assume that the estimates of Pilot PN phases contain multipath errors. In that case, conventional processing leads to considerable location error.

Based on statistic processing of a sequence of measurements, the algorithm described in this paper will determine reliability of measurements of Pilot PN phases and give lower weight to less reliable estimates. As a result, the reliability of the position estimate becomes higher and the location error will be reduced.

3. Estimation of the hybrid network-based algorithm

3.1 System model

Based on the data listed in this paragraph, MS location is estimated. Assume the MS receives known pilot signals from N BTSs.

Let MS receives $t_i, i = \overline{0, N-1}$ times of arrival of pilot signals from these BTSs. These time samples are obtained in the time scale of MS i.e. by MS time and have the titles of signal pilot phases. MS estimates TDOA of BTS signal, which is relative to TOA of master BTS signal, which we will denote by t_0. Thus, the following estimates are generated :

$$\hat{\tau}_{i+1} = t_{i+1} - t_0,\quad i = \overline{0, N-2} \tag{1}$$

Assume that except the estimates (1), $\hat{\tau}_0$ of time of signal traveling from the master BTS to the MS is known.

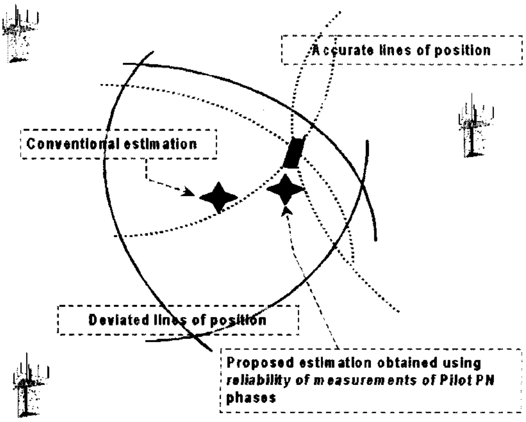
The column-vector of estimates, by which the MS location has to be estimated, is denoted by

$$\hat{\tau} = (\tau_0, \ldots\ldots\ldots, \hat{\tau}_{N-1})^T .$$

3.2 Algorithm of MS location estimation

Assume that for MS position estimate generation, it is possible to use J serial measurements $\hat{\boldsymbol{\tau}}_j,\ j = \overline{1, J}$ of vector $\hat{\boldsymbol{\tau}}$. What is more, MS position is assumed to remain unchanged for the time of obtaining these estimates. Then, the vector of estimate $\hat{\boldsymbol{\tau}}_j$ can be presented as a sum of the vector of true values of signal delays $\boldsymbol{\tau}(\mathbf{x})$ corresponding to MS position $\mathbf{x} = (x, y)$ and measurement errors $\boldsymbol{\delta}_j$

$$\hat{\boldsymbol{\tau}}_j = \boldsymbol{\tau}(\mathbf{x}) + \boldsymbol{\delta}_j \tag{2}$$



(Figure 4) Expectation of proposed estimation

Measurement errors can be presented as a sum of errors of rounding of the delay $\boldsymbol{\delta}_{\mathrm{r}j}$, errors of estimation due to mistiming $\boldsymbol{\delta}_{\mathrm{n}j}$ and multipath errors $\boldsymbol{\delta}_{\mathrm{m}j}$

$$\boldsymbol{\delta}_j = \boldsymbol{\delta}_{\mathrm{r}j} + \boldsymbol{\delta}_{\mathrm{n}j} + \boldsymbol{\delta}_{\mathrm{m}j} \tag{3}$$

The components $\boldsymbol{\delta}_{\mathrm{r}j}$, $\boldsymbol{\delta}_{\mathrm{n}j}$ and $\boldsymbol{\delta}_{\mathrm{m}j}$ of the combined error $\boldsymbol{\delta}_j$ are of different nature. Hence, in general, distribution of the combined error is not Gaussian and can be considered unknown.

One of the most preferable methods of estimation with unknown error distribution is the least square method [9]. According to the method, the MS location estimate can be found as a point of minimum of the following function of cost.

$$\hat{\mathbf{x}} = \min_{\mathbf{x}} \left[\tilde{\boldsymbol{\tau}} - \boldsymbol{\tau}(\mathbf{x})\right]^T \mathbf{W} \left[\tilde{\boldsymbol{\tau}} - \boldsymbol{\tau}(\mathbf{x})\right] \tag{4}$$

There are a number of Cost Function Minimization methods. However, one of the simplest and most efficient algorithms is the Consecutive Search Method.

This algorithm works in two steps:

- Calculation of the cost function within the multitude of points in the uncertainty range of the MS Position(Search area).

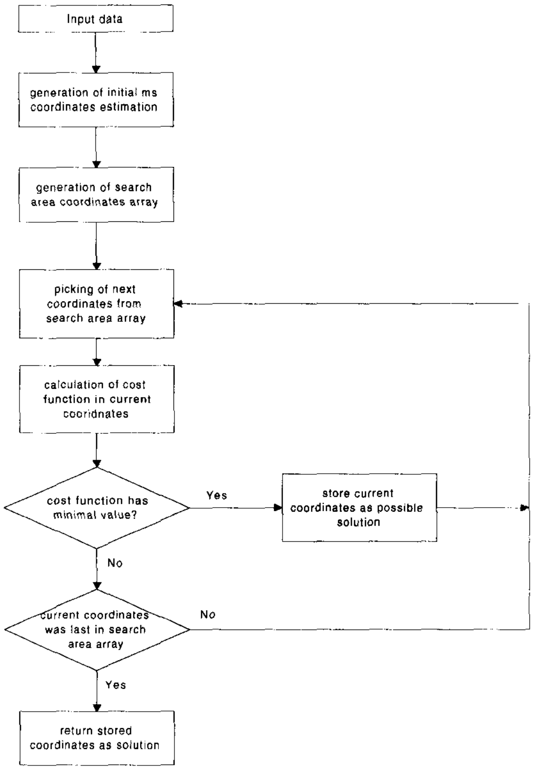
- Subsequent selection of the point in which the cost function takes the minimum value.

The uncertainty range can be selected as a multi-dimensional sphere with some relatively small radius around the original position(estimated) of the mobile station.

Figure 5 shows the block-diagram of the consecutive search algorithm.

The inputs to the algorithm are:

- A set of pseudorange measurements from the BS
- Variance estimation of pseudorange measurements



(Figure 5) the block-diagram of the consecutive search algorithm

- BS Coordinates
- Information about serving BS Sector, in which the MS is situated(optional)
- RTD measurements(optional).

The output from the algorithm is:

- MS Position estimate $\hat{\mathbf{x}}$ in which the cost function takes on the minimum value.

If we know the estimate vector $\hat{\boldsymbol{\tau}}_j$ we can calculate $\tilde{\boldsymbol{\tau}} = \frac{1}{J}\sum_{j=1}^{J}\hat{\boldsymbol{\tau}}_j$ averaged estimate of the signal delay vector of the base station.

Here $\tilde{\boldsymbol{\tau}} = \frac{1}{J}\sum_{j=1}^{J}\hat{\boldsymbol{\tau}}_j$ averaged estimate of BTS signal delay vector.

3.3 Algorithm Validation

If Gaussian errors with zero mean $\boldsymbol{\delta}_n = \frac{1}{J}\sum_{j=1}^{J}\boldsymbol{\delta}_{nj}$ dominated in the system, distribution of the combined error can be considered Gaussian and the estimate (4) is a maximum likelihood estimate [10,11] with

$$W = K^{-1} \qquad (5)$$

where $K = \langle \boldsymbol{\delta} \cdot \boldsymbol{\delta}^T \rangle$ - correlation matrix of errors $\boldsymbol{\delta} = \frac{1}{J}\sum_{j=1}^{J}\boldsymbol{\delta}_j$

If measurement errors can be considered independent, we will obtain an estimate as

$$\hat{\mathbf{x}} = \min_{\mathbf{x}} \sum_{i=0}^{N-1} \frac{1}{\sigma_i^2}(\tilde{\tau}_i - \tau_i(\mathbf{x}))^2 \qquad (6)$$

where σ_i^2 -variance of estimate of time delay of signal from the i-th BTS, $\tilde{\tau}_i = \frac{1}{J}\sum_{j=1}^{J}\hat{\tau}_{i,j}$ Variance σ_i^2 is unknown and can be estimated as

$$\hat{\sigma}_i^2 = \frac{1}{J}\sum_{j=1}^{J}\left(\hat{\tau}_{ij} - \hat{\tau}_j\right)^2$$

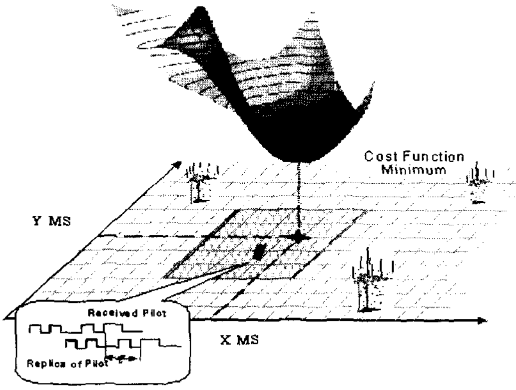
It is a fact that, only in case of Gaussian Error Distribution, the estimate as in equation (6) has a minimum variance and is asymptotically non-offset with unrestricted increase in SNR(Signal to Noise Rate)[9].

It is possible to successfully apply equation (6) to *Non-Gaussian* Error Distribution. If the distribution rule is unknown, then it becomes very difficult to analytically derive the accuracy estimate as in equation 6. It becomes easier to analyze the estimation if a simulation of the same is considered.

During simulation we will assume that the estimate rounding error and the error caused by multipath signal propagation are dominant, which corresponds to CDMA cellular systems.

3.4 Simulation result

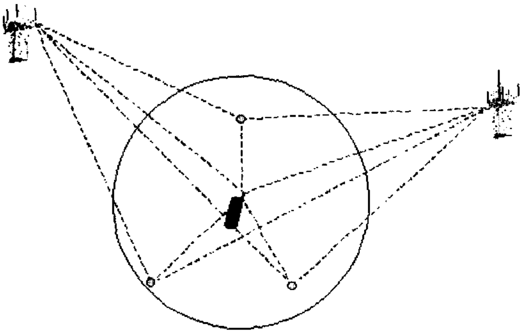
It is known, that the main reason for the multipath signal propagation is signal rescattering [10, 11, 12 etc]. The characteristics of the time and angle of distributions of multipath components of the received signal depends on the position of the building [13] , the MS characteristics and the BS heights[11,14]. Macrocells, which are the subject of our research, have a large radius, of the range 1 to 20 Kms [17]. In order to cover such a large zone the BS antenna needs to be set relatively high, so that it is higher than the surrounding buildings. Hence, the primary reason for multipath within Macrocells is the signal scattering because of scattering elements in the vicinity of the MS, for example, the nearby buildings. The presence of such scatters results in the large spreading of the values of the angle of arrival of multipath components[16]. That is the reason for the angle of arrival of multipath components per MS to be assumed as equal. AS for example[15].



(Figure 6) Position determination based on the cost function

To imitate the multipath signal propagation, in the course of simulation, the well-known GBSBCM model (Geometrically Based Single Bounce Circular Model) [15] was considered as the basis for our model. It is assumed that, in this model, scatters are randomly distributed in the range of radius r around the MS. Usually, the equal and Gaussian Distributions of scatters are used. Simulation is carried out by tracing *the paths from the MS to a scatter element and then* to the BS. The following figure clarifies the model that has been used:

During simulation, the circle radius r and the number of scatterers N are determined. Scatterers



(Figure 7) Simulation model

have been placed randomly within a circumference of the radius r. The coordinates of scatterers in Cartesian coordinate system is calculated by the equation,

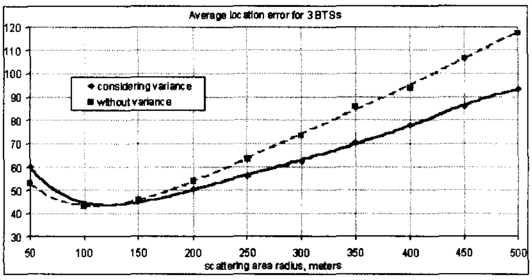
$$x = r \cdot \sqrt{\xi}$$
$$y = 2 \cdot \pi \cdot \zeta$$

where ξ, ζ random numbers uniformly distributed within the range [0, 1].

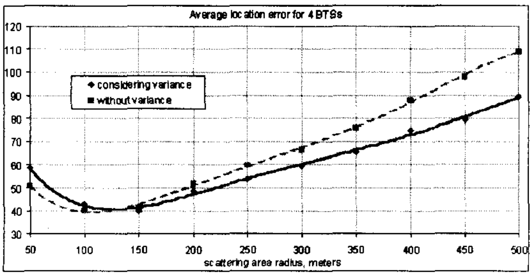
Then, based on the distances MS-scatterer BTS paths, delays have been calculated.

For each BTS related to MS location, the portion of Line Of Sight(LOS) path power has been randomly selected out of the total signal power $\eta \in [0,1]$. Considering the portion of LOS path power, the amplitudes of received paths have been determined by the equations

$$A_{LOS} = \sqrt{3 \cdot \eta} \cdot \xi$$



(Figure 8) Average location error for 3 BTSs



(Figure 9) Average location error for 4 BTSs

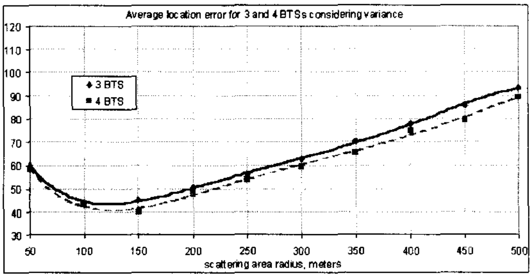
$$A_S = \sqrt{\frac{3 \cdot (1-\eta)}{N}} \cdot \zeta$$

where ξ, ζ random numbers uniformly distributed within the range [0, 1].

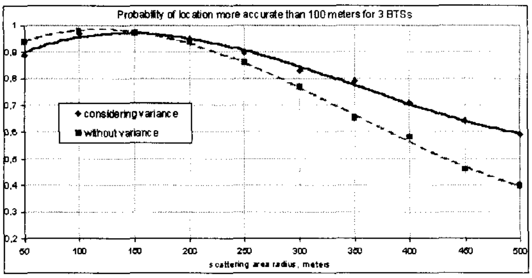
16 estimations of signal traveling from BTS to MS have been carried out to determine coordinates. Based on the estimates, considering time resolution of measurements in real systems, averages of TOA and TDOA have been determined.

Coordinate determination has been simulated in the least square method, considering both variance of the TOA and TDOA estimation and without variance as described in the report.

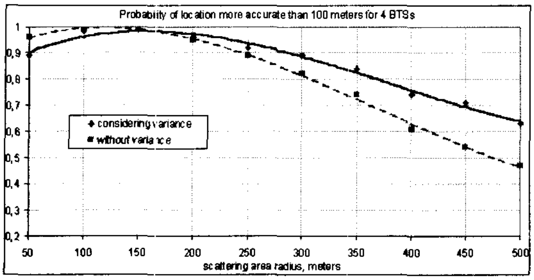
Average location error and the probability of position determination as accurate as less than 100 meters have been simulated for different r. Simulation results for location of three and four BTSs are given below.



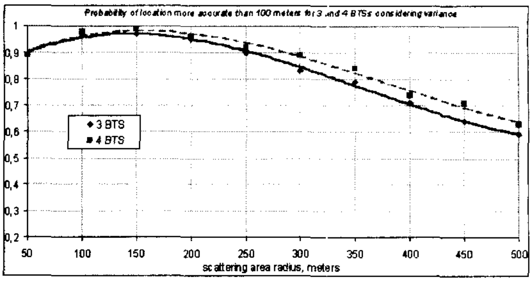
(Figure 10) Average location error for 3 and 4 BTSs considering variance



(Figure 11) Probability of location more accurate than 100 meters fro 3 BTSs



(Figure 12) Probability of location more accurate than 100 meters for 4 BTSs



(Figure 13) Probability of location more accurate than 100 meters for 4 BTSs

4. Conclusion

This paper analyzes the accuracy of non-GPS MS position measurement. The necessity of development of such a network-based algorithm arises when the position of cdma2000 1x standard-compliant MSs that do not include GPS receiver has to be determined. The main method of determining position of such MSs is to measure difference of time of arrival of pilot signals from several BTSs by MS. Given such an approach, there are two major factors that limit accuracy of MS position measurement. The first one is error of signal time delay measurement caused by multipath signal propagation. The second one is a limitation and extremely low resolution power of the algorithm that is used in MS for estimation of signal delay time. The latter introduces uncertainty into MS position of about 120 meters. Due to the described reasons, the existing position estimation algorithms based on one time measurement of time delays cannot reach the required estimation accuracy.

The paper has proposed to use a sequence of delay estimates for the purpose of compensation for rounding error and random component of multipath error. What is more, to compensate for the systematic multipath error and joint processing of delay estimates obtained from a sequence of measurements, it is proposed to use the least square method. The least square method is a simple solution when it is hard to obtain any information on the type of distribution of delay measurement error and the significantly different measurement accuracy of signal delays of different BTSs should be considered.

Simulation has shown that if the proposed approach for MS position determination is used, estimation accuracy becomes greater than the one specified by the standard even with small(that is 1/16 chip measurement) number of measurements, and that a network-based location system holds promise for meeting the FCC requirements for location accuracy in cdma2000 1x. Hence the described network-based algorithm can be successfully applied to cdma2000 1x MS position determination.

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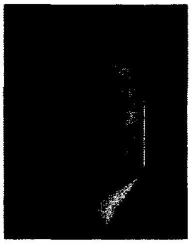

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